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Deployment of Wireless Sensor Networks in Logistics – Potential, Requirements, and a Testbed

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***Abstract*—With the growing demand for extensive monitoring of transport processes in logistics and approaches for an event-based management of logistics processes, wireless sensor network technology has become a promising technology for this domain. In the first part of this paper, we describe such application possibilities for wireless sensor networks in logistics and focus on supply chain event management as one particularly promising application area, which is often neglected. Afterwards, we present first findings regarding the requirements to be considered for efficient application of wireless sensor networks in logistics. We especially differentiate the design decisions into decisions for the design-time and the run-time of a wireless sensor network deployment in the logistics domain. As such deployments can hardly be tested in real-life scenarios due to organizational and cost reasons, we have built a small-scale testbed. This testbed is presented in the last section of this paper.**

I. INTRODUCTION

Wireless sensor nodes (*motes*) and wireless sensor networks (*WSNs*) offer a variety of capabilities, which make their deployment very promising for several application areas (cf. e.g. [1], [2]), with logistics being one of them, as outlined in Section II. Logistics processes in general and supply chain event management (*SCEM*) in particular can significantly benefit from the sensing and communication possibilities of WSNs. For example, environmental parameters influencing the conditions of transported goods, like tilt, shock, humidity or temperature, can be monitored during the transport process. In case critical values are detected an alarm message with the corresponding event data can be transmitted. Thus, with a deployed WSN such before mentioned events can be detected early and directly at their point of origin during the transport. Additionally, a corresponding notification of relevant decision makers becomes possible using the communication capabilities of the deployed WSN.

For a beneficial exploitation of the existing possibilities, several requirements have to be considered. Consequently, we have examined four requirement categories for the use of WSNs in logistics, which are presented in Section III. These requirements influence criteria concerning the initial design of a WSN in logistics (design-time), as well as decisions concerning the concrete operation of a WSN in logistics during run-time (Section IV). The evaluation of corresponding solutions can hardly take place during normal operations of a freight carrier due to organizational reasons and cost considerations. Therefore, we developed and installed a testbed at the Multimedia Communications Lab (KOM) at Technische Universität Darmstadt (TUD). The testbed can be used for evaluation purposes besides simulation to incorporate real world problems and factors of influence not modelled in simulation tools (cf. e.g. [3]).

II. WSNS IN LOGISTICS – POTENTIAL USE

Several application possibilities for WSNs in the domain of logistics have already been identified. Some initial application possibilities in the context of storage logistics have been described [4], but most often a monitoring of transport processes in the context of transportation logistics is envisioned. Naturally in this context, cold chain monitoring and food logistics are a main focus [5], [6]. One example is the intelligent container [7]. Jedermann et al. use a distributed platform of interacting software agents in combination with a processor module, an RFID system and a WSN deployed in a container. With this system, they want to achieve an autonomous control of transport processes.

We expect SCEM as one particular promising application area for WSNs in the domain of logistics. SCEM can be understood as a management concept as well as a (software) system supporting this management concept [8]. The focus is laid on the detection of so-called events. In this context, events are understood as essential state changes for certain addressees [9]. These events constitute the basis for the management of the supply chain. Their occurrence indicates the requirement for a management action. Thus, a management concept is implemented which leans on the concept of management-by-exception. This management concept needs to be supported by a corresponding (software) system, hence leading to the (software) system perspective of SCEM. SCEM incorporates the five functions 'monitor', 'notify', 'simulate', 'control' and 'measure' [8], which are executed in this sequence (Fig. 1).

With the sensing, processing and data transmission capabilities of WSNs, we expect that the monitor function, the notify function and the measure function can substantially be supported. The sensing units of motes deployed in a container or a truck's load area can monitor environmental parameters critical for the condition of transported goods. On this basis, the processing units can execute target-performance comparisons to detect events, e.g. in the form of violation of predefined thresholds. Thus, a significant support of the monitor function can be reached. In case an event is detected, the corresponding information can be transferred through the

WSN and appropriate gateways to responsible decision makers (cf. Section IV), realizing the notify function. Finally, with the available storage capacity on the motes in the WSN, a history of measured environmental parameters and events can be preserved. These can be used as performance indicators in the sense of the measure function to facilitate an assessment of the monitored transport process.

III. Requirements for the Use of WSNs in Logistics

In Section II, we have presented possibilities for the use of WSNs in the domain of logistics. To realize the described potential inherent by this technology, several requirements have to be considered. As these requirements have quite different origins, we distinguish four different categories of requirements:

- Technological Requirements: Comprises properties and constraints of the applied technology, e.g. energy constraints of WSNs.
- Economical and organizational requirements: Comprises economical constraints and potential needs for the integration in an existing infrastructure, e.g. cost-benefit ratio for deployment of WSNs.
- Regulatory requirements: Comprises constraints by law and standardization bodies, e.g. usable frequency bands for transmission.
- Logistics market specific requirements: Comprises properties and constraints of the application domain, e.g. massive cost pressure.

Additionally, interdependencies and conflicting goals between these requirement categories exist. For example, a redundant deployment of motes is preferable as a consequence of technological requirements to ensure functionality despite individual mote failures. But, this implies higher costs, conflicting with logistics market specific requirements.

As we have seen in Section II, enhanced information availability can be exploited in several ways and can lead to significant benefits. But this enhanced information availability realized by WSNs does not come for free. Therefore, and especially against the background of the massive cost pressure

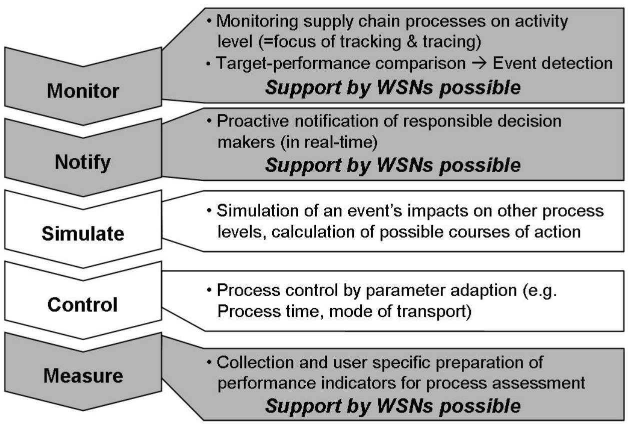

Fig. 1. Functional components and possible WSN support of SCEM systems (based on [8])

in the logistics market, a sufficient cost-benefit ratio must be ensured as part of the logistics market specific requirements. Consequently, a thorough and detailed investigation of the economical value of a specific WSN deployment in a logistics context should be mandatory. Unfortunately, most often a technological view focussing on technological requirements only is chosen.

IV. Design-Time and Run-Time Design Decisions

Designing a WSN deployment several design questions have to be answered and corresponding decisions have to be taken. These design decisions can be divided in decisions concerning the initial layout of the WSN (design-time) and decisions concerning the operation of the deployed WSN (run-time). In the following, we will focus on decisions for the design-time and cover run-time decisions just shortly.

A. *Design-Time Decisions*

With a WSN being formed by collaborating autonomous motes and understanding that in the described application context the WSN-data is needed at several end users respectively their systems, amongst other decisions, fundamental selections of platform, number of motes, location of motes, and connectivity must be made.

All these design decisions have to be taken against the specific application background, in our case transport processes in the domain of transportation logistics, and taking into account the requirement categories described in Section III. So, for example to answer the question which motes should be used, there has to be a decision which environmental parameters have to be monitored, how much money can be spent and so on. As no generally applicable solution exists, we do not provide a generic solution at this point. Instead, we focus on the network connectivity next and address the question on how a connection between a WSN and an end user, in our case the decision maker responsible for reaction to an occurred event during the transport, can be established.

We have identified two basic alternatives to establish a connection between a WSN deployed in a container on a truck or a truck's load area and a decision maker responsible for the corresponding transport process: The connection can be established by using devices already available in the truck and able to establish a long-distance connection to the end user's system (Fig. 2) or by employing dedicated devices just for connecting the In-Truck-WSN with the decision maker's system (Fig. 3).

It is very probable that the truck driver at least possesses a simple cell phone or already a smartphone. Otherwise, he can easily be equipped with one. Consequently, it can be assumed that such a device is available to be used to connect the WSN to the end user's system. Besides, many trucks carry a so-called On-Board-Unit (OBU), which is for example needed for toll accounting. These are two different devices which could be used to establish a connection between WSN and the end user.

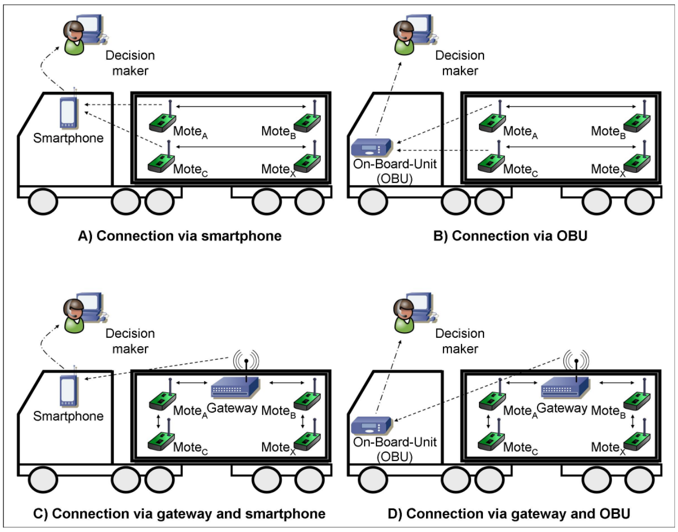

Fig. 2. Possibilities for connection of an In-Truck-WSN to end users via existing devices

Besides using such already existing devices, another option would be the deployment of dedicated, specialized gateways, solely used for the connection between WSN and end user.

Regarding the economical and organizational requirements as well as the logistics market specific requirements with their massive cost pressures and the corresponding cost-efficiency needed, a usage of already existing devices seems very promising. This would imply the use of a smartphone or the OBU. In addition to the capability to establish a long-range connection to the end user, a smartphone would feature a well-known and easy-to-use interface to the truck driver. This interface would allow giving the driver instructions directly in case critical parameters are detected. So, smartphones seem to be very promising devices for the connection of an In-Truck-WSN to an end user's system. Furthermore, a smartphone would provide additional computing and storage resources, as well. These could be used for example for aggregation of data received from the WSN. As a consequence, we think that in future research possibilities to connect In-Truck-WSNs with smartphones should be pursued intensely.

B. Run-Time Decisions

Taking the requirement categories of Section III as a basis, two criteria for the run-time of a WSN deployed in logistics can be identified as most important:

- Energy-efficient operation as a result of technological requirements

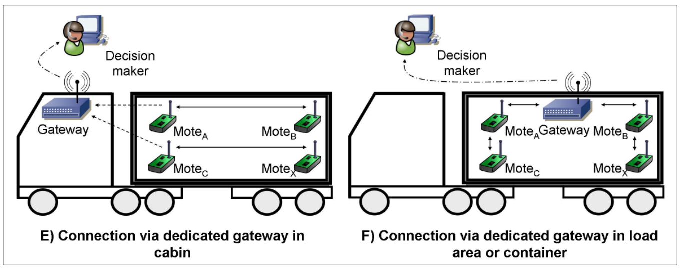

Fig. 3. Possibilities for connection of an In-Truck-WSN to end users via specialized gateways

- Cost-efficient operation as a result of logistics market specific requirements

We address these criteria with the concept of so-called *transmission-relevant events*. In the domain of logistics and especially in the context of SCEM events are understood as essential state changes for certain addressees (cf. Section II). As transmission-relevant events, we specify events, which possess an information value higher than their transmission costs. Thereby, our understanding of transmission costs comprises costs in terms of energy and in terms of money. So, in case an event is detected by a mote, it uses current context data and further information to decide whether it is a transmission-relevant event or not and only transmits data of transmission-relevant events. This way, we expect to significantly enhance both energy-efficient operation and cost-efficient operation of WSNs deployed in transport processes.

V. Testbed Design

Solutions and approaches in the context of WSNs in transport processes cannot be tested during regular operations of a freight carrier due to organizational and cost reasons. Hence, we have developed a testbed at KOM at TUD, which can be used besides simulation to test solutions and approaches in a more realistic setting, incorporating some real world problems and factors of influence not modelled in simulations.

To support intermodal transportation scenarios, small-scaled models of different means of transport, like containerships, trucks and trains, as well as containers have been deployed in a modelled landscape with various transport routes featuring different characteristics (Fig. 4). Thus, we currently provide a transportation scenario starting with the arrival of a container at a port which is then transported either only by truck or by train and truck to a warehouse as the point of destination. Currently, we have equipped the model containers with SunSPOTs as they are easy to program, provide all sensor capabilities needed for our purposes, are well supported and documented, possess a wide dissemination in the community, and are relatively cheap. Naturally, if the detailed analysis of the design questions mentioned in Section IV or gathered experience should yield that SunSPOTs are not suited anymore, we could switch to other mote platforms as well. Environmental parameters relevant for a wide variety of transported goods, e.g. high value consumer electronics like plasma screens, pharmaceuticals and medicine like swine flu vaccine or food like bananas, are tilt, shock and temperature. Thus, we currently test their influence and provide real-time monitoring of these critical parameters with the deployed SunSPOT-infrastructure. Changes of these parameters are modelled by the influence of the characteristics of different transport routes. For example, we deployed a model bridge, which causes tilt changes when used in the context of a container transport by truck. Furthermore, we have deployed model roads with potholes, causing sudden shocks. And finally, we have deployed an infrared lamp which can be used to change the temperature of the interior of the container. Additionally, we use an RFID infrastructure with six RFID-readers installed at the different transshipment points and the warehouse as point of destination combined with the corresponding tags applied to the model container. This way, tracking and tracing of the model container as it is transported from the port to the warehouse is implemented, as well.

Currently, we focus on run-time behaviour with testing possibilities for real-time monitoring of the transport process of our model container through our test scenario. Furthermore, possibilities for event detection and transmission with WSNs in logistics are analyzed. In the future, we plan to integrate some possibilities to evaluate design-time decisions as well, for example by integrating mobile devices like smartphones to test possibilities for their connection with a WSN (cf. Section IV).

VI. Related Work

The application of WSNs in the logistics domain is a main research aspect of Jedermann and his colleagues involved in the Collaborative Research Centre 637 “Autonomous Cooperating Logistic Processes”[1] located at the University of Bremen. Their focus is on developing an intelligent container, equipped with a processor module, an RFID system and a WSN. Using this intelligent container and software agents they work on realizing autonomously controlled transport processes with a distinct focus on food and cold chain logistics. Ruiz-Garcia et al. are focussing their work on WSNs in logistics on food and cold chain logistics, too [5], [10]. In this context, they research energy-efficient design of motes and communication infrastructures of WSNs. Evers et al. have as well chosen logistics as application scenario for their work in WSNs [11]. They too address energy efficiency, but regarding reprogramming of motes for which they provide an energy-efficient, secure, flexible and dynamic solution.

The described research work mostly adopts a strong technological view, primarily addressing technological requirements. Logistics market specific requirements are rarely considered or only on a rather basic, very abstract level.

VII. Conclusions and Outlook

We have identified the potential use for WSNs in the context of supply chain event management as significant and very promising. To realize this potential with the deployment of a WSN in the logistics domain, requirements of the categories technological requirements, economical and organizational requirements, regulatory requirements and logistics market specific requirements as well as their interdependencies have to be considered. These requirements influence both decisions concerning the design-time of a WSN and concerning the intended run-time behaviour of a WSN. Several of the design decisions to be taken have been described. As one of these, possibilities to connect an In-Truck-WSN to end user systems have been investigated exemplary. As a result, we identified the connection via smartphone as a very appealing approach, which should be investigated in more detail in future work. Finally, we have described our testbed and presented it as one possibility to evaluate approaches in the context of WSN deployments in logistics processes.

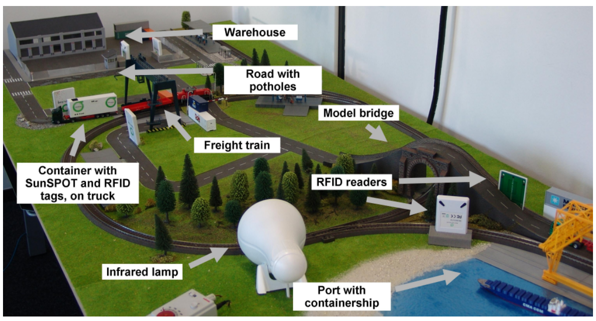

Fig. 4. Model of application scenario used as testbed

[1] http://www.sfb637.uni-bremen.de

In the next steps, the described design questions concerning design-time and run-time of a WSN to be deployed in a logistics process have to be analyzed in more detail. This has to be done considering the background of the mentioned requirement categories and clearly with a broadened focus not just addressing technological requirements, but explicitly taking into account logistics market specific requirements, as well. The resulting solutions will be evaluated in our testbed.

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